



A new Monte Carlo Generator for Ultra-High Energy Cosmic Rays from the Local and Distant Universe

KLAUS DOLAG¹, MARTIN ERDMANN², GERO MÜLLER², DAVID WALZ², TOBIAS WINCHEN²

¹ *MPI für Astrophysik, Garching, Germany*

² *III. Physikalisches Institut A, RWTH Aachen University, Germany*

tobias.winchen@physik.rwth-aachen.de

Abstract: For the understanding of the origin and propagation of ultra-high energy cosmic rays (UHECR) we developed a new approach to simulating UHECRs from an arbitrary number of sources based on Monte Carlo technique. The method consists of a combination of three steps. For distant sources we apply commonly accepted parameterizations to calculate the contribution to the observed cosmic ray flux. For sources of the local universe we use forward tracking through realistic matter distributions and magnetic fields resulting from explicit simulations of large-scale structure formation. From the calculations and the forward tracking we generate maps of the probability to observe a particle with a given energy from a discrete direction. To account for deflections in the galactic field, these probability maps are transformed by matrices calculated from backtracking of antiparticles through field parameterizations. Based on the combined probability maps, Monte Carlo production of individual UHECR data is performed which are then used in comparisons with UHECR measurements. The simulated UHECR data serves for optimizing the analysis techniques used in UHECR measurements as well as for constraining the parameter space of the underlying source and magnetic field models.

Keywords: UHECR Propagation, Monte Carlo simulations

1 Introduction

The comparison of observations with model predictions by means of Monte Carlo generated data can be a powerful tool to improve the knowledge on the origin and propagation of UHECRs. Currently there are basically two approaches to this challenge.

In the first approach UHECR data are generated by a full forward simulation of the UHECR propagation from their sources to the observer, accounting for energy losses and deflections in magnetic fields at every point of the trajectory. The low rate of trajectories hitting the observer renders the generation of large datasets by this technique a computationally intensive task. It becomes more and more costly as the source distances increase. Furthermore energy losses due to the expansion of the universe and the corresponding increase of the photon density are difficult to incorporate efficiently.

A second approach uses parametrizations for the energy losses and deflections in magnetic fields and is hence much less computationally intensive than the full forward simulation. These parametrized simulations however cannot easily describe structured extragalactic magnetic fields as expected from large-scale structure simulations. Furthermore the commonly used parametrizations are the result of an averaging process over long propagation distances and are thus not reliable on short propagation distances. How-

ever, energy losses due to the expansion of the universe and the changes in the photon fields can be easily included.

In the following we present a combination of both approaches for the propagation of protons. For the UHECR flux from sources up to a distance of 110 Mpc, in the following called the *local universe*, we track individual particles using matter distributions and magnetic fields from constrained simulations of large-scale structure formation. The size of this simulation regime is determined by the size of the structure simulations at hand. Furthermore a current proper distance of 110 Mpc correspond to a red shift of $z = 0.027$ or a scaling factor of $R = 0.97$ respectively. Neglecting the increased energy losses and only accounting for cosmic time dilation the luminosity of sources in the maximum distance is overestimated by at least 3% depending on the magnetic field strength.

2 Forward simulation

The magnetic fields and source distributions used in the forward simulation are the result from simulations of Λ CDM large scale structure formation [1]. The simulations have been constrained using data from the IRAS 1.2Jy Redshift Survey [2] to reproduce the observed distribution of luminous matter. These simulations have been combined with simulations of the magneto hydrodynamic evolution of a

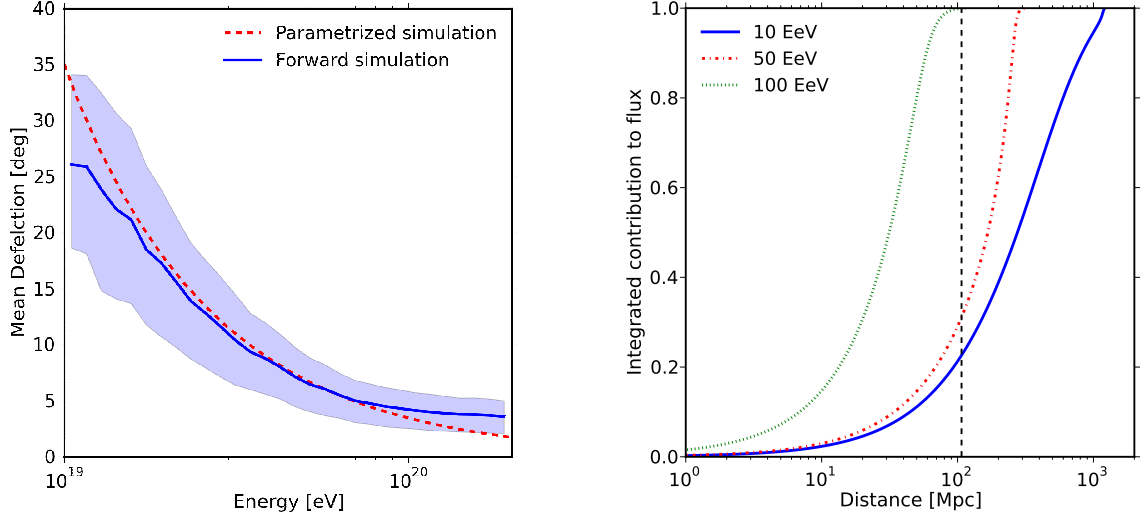


Figure 1: Average deflection strength of the forward simulation of UHECRs from sources in 107 Mpc distance in an exemplary local universe and best fit of simulations with PARSEC (left panel). Integrated contribution from sources up to distance d to the flux for different energies (right panel). The vertical dashed line denotes the merging point of the two simulation regimes.

primordial seed field. The resulting magnetic fields are shown to be compatible with observations by means of synthetic Faraday measurements.

In our simulations UHECRs are injected at point sources with a distribution following the distribution of matter in the large-scale structure simulation. The trajectories of the UHECRs from the source to a spherical observer in the center of the simulation region are calculated using a modified version of the CRPropa software [3, 4].

The size of the observer dominates the detection rate of UHECRs in the forward simulation. Larger observers however introduce systematic errors in the deflection angles due to the geometric distortion and reduced propagation path lengths. To account for these effects and also ensure a high performance we adapt the observer size to the distance of the source such that the systematic error on the deflection remains below 2 deg.

The simulations of the large-scale structure are performed in the smoothed particle hydrodynamics formalism. To avoid computationally expensive calculations we precalculate the magnetic field from the smoothed particle data on a regular cubic grid with 100 kpc distance between nodes. The magnetic field at arbitrary positions is then calculated using trilinear interpolation between the values at the nodes of a cell. The grid spacing of 100 kpc however results in a data size of 150 GB for the complete grid. To avoid swapping due to the limited memory of typical desktop PCs, the grid is divided into cubes with an edge length of 20 Mpc. The resulting memory load of ca. 1 GB for the magnetic field can be easily handled by current desktop PCs. All UHECRs in one box are first propagated to the

edges of the cube. Second the next cube is loaded into memory and all corresponding UHECRs are processed. The processing of the individual cubes is optionally parallelized on several CPUs. To further improve the performance, UHECRs with a propagation distance larger than 1.5 times the linear distance between observer and source are dropped. Only about 1 per mille of the UHECRs are lost owing to this cut [4].

3 Parametrized simulation

For the propagation in the distant universe we use the PARSEC software [5], which uses parametrizations for the energy loss and deflections in turbulent fields to calculate a map of the probability to observe a particle in a discrete direction (pixel) in a given energy bin for extragalactic propagation. To account for deflections in galactic magnetic fields, these probability maps are then transformed using pre-calculated matrices obtained from backtracking of UHECRs through models of the galactic field. Energy losses are modelled within continuous energy loss approximation implementing the attenuation length from [6] in the extragalactic propagation and neglected in our galaxy.

Assuming source spectra following a power law with spectral index γ , the probability to observe a particle in pixel j with energy E_i in the range $E_{l,i} < E_i \leq E_{u,i}$ is

$$p_j^i = \Gamma_i \sum_k \frac{L_k}{d_k^2(1 + \hat{z}_k)} (\hat{E}_{u,i}^{\gamma+1} - \hat{E}_{l,i}^{\gamma+1}) P_{EGMF}(\alpha_{j,k}). \quad (1)$$

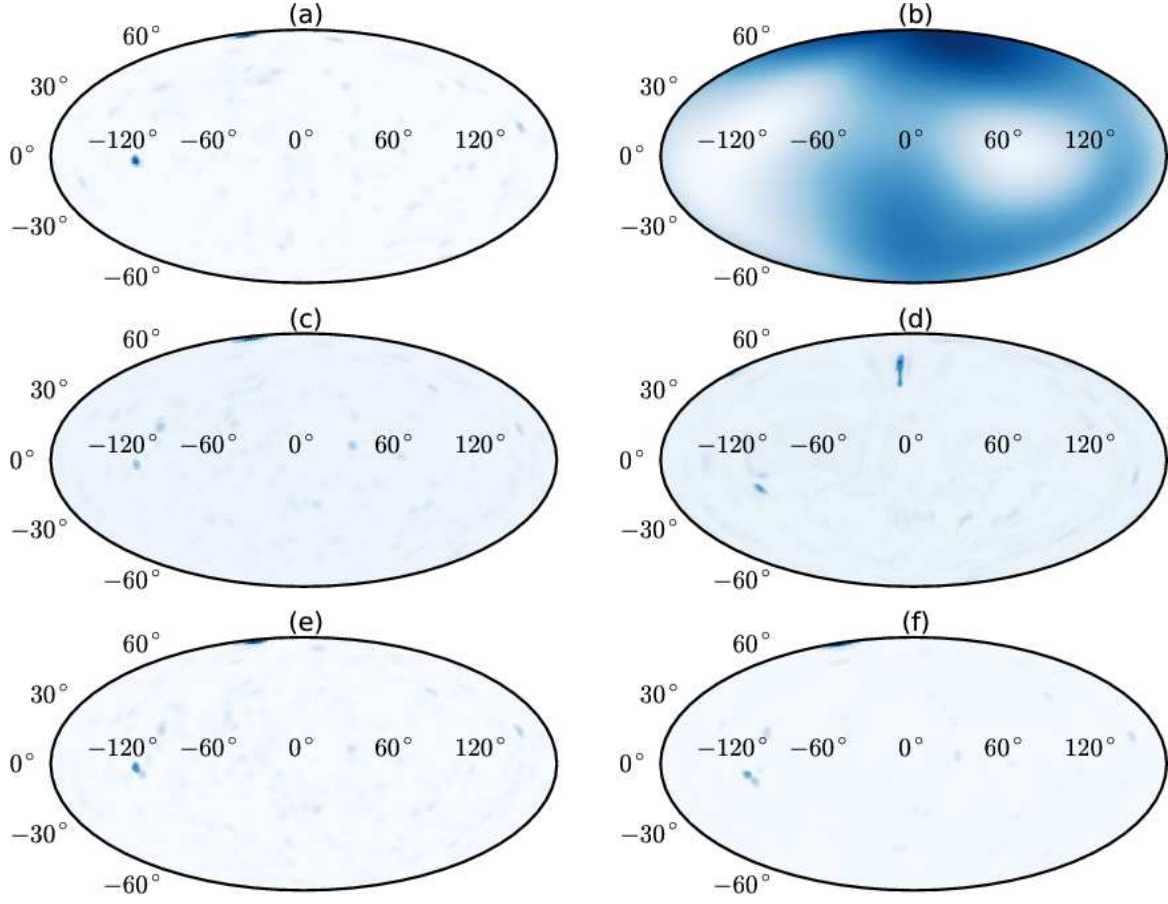


Figure 2: Hammer projected probability density maps in galactic coordinates for an exemplary realization with a source density of $10^{-3.5} \text{Mpc}^{-3}$. Blue indicates higher, white lower probability on an arbitrary scale. **(a)** Forward simulation for 10 EeV. **(b)** Parametrized simulation for 10 EeV. **(c)** Weighted combination of map a) and b). **(d)** Application of a BSS-S [9] type galactic magnetic field to map c). **(e)** Probability map from the forward simulation for 50 EeV. **(f)** Application of a BSS-S type galactic magnetic field to map e).

Here \hat{z}_k is the redshift of the source at time of emission of the particles at source k in current proper distance d_k with luminosity L_k . $\hat{E}_{i,l}$ and $\hat{E}_{i,u}$ denote the energies at the source contributing to the observed energies in the range $E_{l,i} - E_{u,i}$ and include energy losses from photon interaction and expansion of the universe. The factor $P_{EGMF}(\alpha_{j,k})$ accounts for the deflection of the UHECR in extragalactic fields with $\alpha_{j,k}$ being the angle between the direction of pixel j and the direction of source k .

To describe the deflection in the extragalactic magnetic fields we use a Fisher distribution [7] to describe the angular distribution of the UHECRs around the source. The Fisher distribution is the normal-distribution on a sphere and has the functional form

$$f(\kappa, \alpha) = \frac{\kappa}{4\pi \sinh \kappa} e^{\cos \alpha} \quad (2)$$

with concentration parameter κ indicating the width of the distribution and α the angular distance from the center of the distribution. For small concentration parameters κ the Fisher distribution converges to the isotropic distribution. For large κ the Fisher distribution converges to a Rayleigh distribution with width σ and $\kappa = 1/\sigma^2$.

We use $\kappa = 1/\sigma^2$ with

$$\sigma \propto \sqrt{D_k \Lambda} \frac{B}{E} \quad (3)$$

taken from [8] to describe the deflection power in magnetic fields. Here D_k is the distance of source k , Λ the coherence length, and B the strength of the magnetic field. E denotes the energy of the cosmic ray. The elongation of the propagation path due to deflection in the magnetic fields is parametrized based on the work of Achterberg et al. [8], but has been modified to include energy losses in the parametrization [5].

4 Combination of simulation regimes

For a consistent model, the deflection strength of the parametrized simulation has to be scaled to match the mean deflection in the forward propagation. The left panel of figure 1 shows the mean deflection resulting from the forward simulation of 5000 UHECRs from isotropically distributed starting points in 107 Mpc distance in the local universe

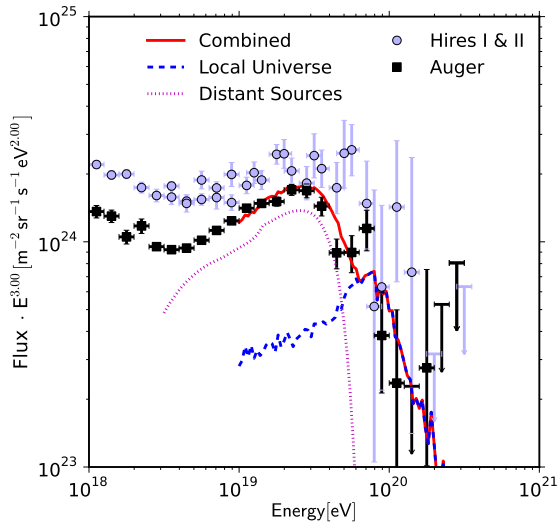


Figure 3: Energy spectrum resulting from the exemplary simulation in comparison with observations from the HiRES experiment [10] and the Pierre-Auger Observatory [11].

and the best fit of the mean deflection strength with PARSEC. The best fit is achieved for $B\sqrt{\Lambda} = 0.94 \text{ nG}\sqrt{\text{Mpc}}$ in equation 3.

Both simulation regimes are combined by means of summing up maps of the probability to observe a particle in a given energy range from a discrete direction. While the probability maps of the contribution from the distant universe are calculated explicitly with PARSEC, the probability maps from the local universe are created from the forward tracking data. The maps are weighted so that the total contribution from the local universe matches the expected contribution from continuous sources in the same volume for the lowest energy bin. This weight is calculated using PARSEC with the matched strength for the magnetic field. The integrated relative contributions over the distance are shown in the right panel of figure 1 for three different energies.

To account for deflections in the galactic field, the resulting probability maps are transformed using the matrix technique provided by PARSEC. From the final probability maps simulated data sets with large numbers of UHECRs are then generated with low computational effort.

5 Results and Conclusion

In figure 2 we show exemplary probability maps from the forward propagation in the local universe and the parametrized simulation in the distant universe together with the combined maps at two energies. The source density in this exemplary simulation is $\rho = 10^{-3.5} \text{ Mpc}^{-3}$, resulting in a total number of 1763 sources in the local uni-

verse and more than 4.4 million sources up to the maximum simulation distance of 1500 Mpc. The source spectra have been set to $\gamma = -2.7$. For an energy of 10 EeV the ratio of the flux from the distant universe to the local universe $N_{\text{near}}/N_{\text{tot}} = 0.23$. For energies above 100 EeV all particles originate from the local universe.

In figure 3 we show the resulting energy spectrum from the exemplary realization calculated using 100 energy bins between $10^{18.5} \text{ eV}$ and 10^{20} eV . For comparison the observed energy spectra of the HiRES experiment [10] and the Pierre-Auger Observatory [11] are also shown. The simulated spectrum is normalized to match the observation of the Pierre Auger Observatory at 10 EeV.

With the technique presented in this contribution we have developed a promising mechanism for the extensive production of Monte Carlo simulations of UHECRs suitable for studies of anisotropy and cosmic magnetic fields. The simulation includes effects of structured extragalactic and galactic magnetic fields, as well as energy losses and arbitrary source configurations.

References

- [1] Dolag, K., Grasso, D., Springel, V., and Tkachev, I. (2005) *Journal of Cosmology and Astroparticle Physics* **01**, 009.
- [2] Fisher, K. B. et. al. (1995) *Astrophysical Journal Supplement* **100**, 69.
- [3] Armengaud, E., Sigl, G., Beau, T., and Miniati, F. (2007) *Astroparticle Physics* **28**, 463–471.
- [4] Erdmann, M., Müller, G., Schiffer, P., Walz, D., and Winchen, T. (2011) *In preparation*.
- [5] Erdmann, M., Schiffer, P., and Winchen, T. (2011) *In preparation*.
- [6] Protheroe, R. J. and Johnson, P. (1996) *Astroparticle Physics* **4**, 253.
- [7] Fisher, R. (1953) *Proceedings of the Royal Society A* **217**, 295–305.
- [8] Achterberg, A. et. al. (1998) In 19th Texas Symposium on Relativistic Astrophysics and Cosmology Paris, France
- [9] Harari, D., Mollerach, S., and Roulet, E. (1999) *Journal of High Energy Physics* **08**, 22.
- [10] HiRes Collaboration (2008) *Physical Review Letters* **100**, 101101.
- [11] The Pierre Auger Collaboration (2010) *Physics Letters B* **685**, 239–246.